

Satellite Remote Sensing for Malaria Epidemic Early Warning in a Highland Region of Ethiopia

Michael C. Wimberly¹

Alemayehu Midekisa¹, Ting-Wu Chuang¹, Geoffrey M.
Henebry¹, Yi Liu², Gabriel Senay¹³

1 Geographic Information Science Center of Excellence,
South Dakota State University

2 Dept. of Electrical Engineering and Computer Science, South
Dakota State University



3 USGS Center for Earth Resources Observation and Science (EROS)

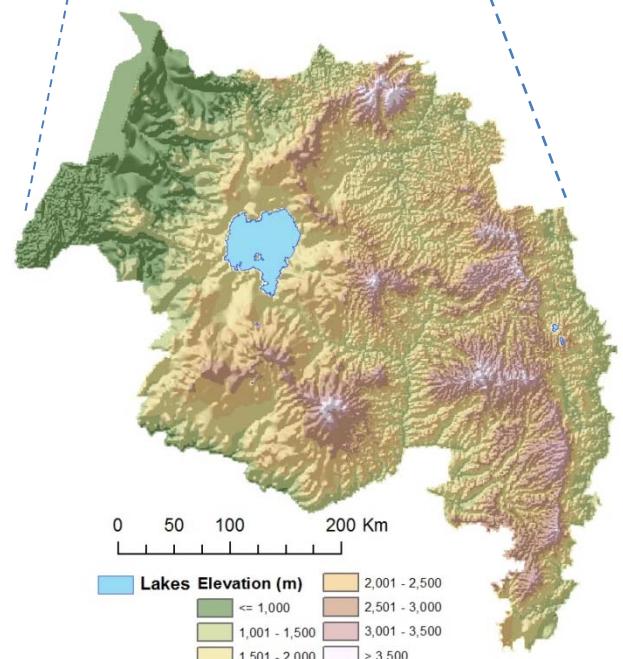
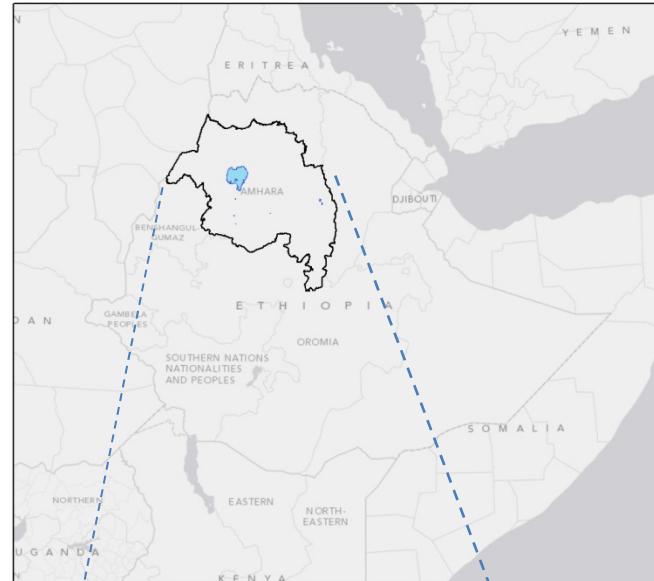


Outline

- Exploratory analysis of historical malaria surveillance data (Wimberly et al., 2012, *Tropical Medicine and International Health*)
- Time series analysis of climatic influences on historical malaria cases using remotely-sensed data (Midekisa et al, 2012, *Malaria Journal*)
- Remotely-sensed environmental risk factors for malaria outbreaks (Wimberly et al., 2012, *Proceedings of the International Congress on Environmental Modelling and Software*)

Study Area: Amhara Region of Ethiopia

- Size: 157,000 km² (78% of SD)
- Population: > 18 million (2,234% of SD)



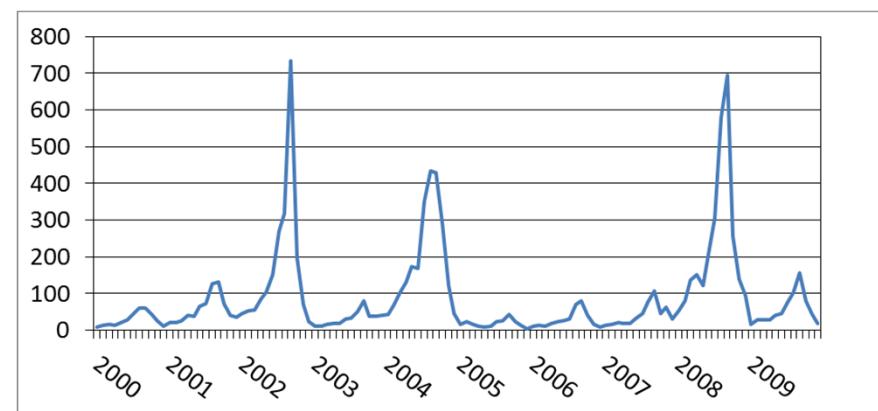
Background – Epidemic Malaria

- Malaria is a leading public health problem in sub-Saharan Africa
- Ethiopia
 - More than 2/3 of the population at risk
 - 9-15 million malaria cases per year
- Epidemic versus endemic malaria
 - 114,000 deaths during the last major epidemic in Ethiopia (2003)



Background – Disease Forecasting

- Public health strategies for disease control and prevention
- Challenge of planning for disease epidemics and other “unpredictable” events
 - Risk of not responding
 - Risk of overresponding
- Importance of accurately forecasting future disease outbreaks



Exploratory Analysis of Malaria Surveillance Data

- Are different malaria surveillance variables (e.g., clinically diagnosed versus confirmed malaria cases) correlated with one another?
- Temporal patterns – how does malaria risk vary over time?
- Spatial patterns – how are malaria cases distributed in space?
- Spatio-temporal patterns (synchrony) – are malaria outbreaks entirely local, or are they synchronized across larger areas?

Tropical Medicine and International Health
doi:10.1111/j.1365-3156.2012.03058.x
VOLUME 17 NO 10 PP 1192–1201 OCTOBER 2012

Spatial synchrony of malaria outbreaks in a highland region of Ethiopia

Michael C. Wimberly¹, Alemayehu Midekisa¹, Paulos Semuniguse², Hiwot Teka³, Geoffrey M. Henebry¹, Ting-Wu Chuang¹ and Gabriel B. Senay⁴

¹ Geographic Information Science Center of Excellence, South Dakota State University, Brookings, SD, USA
² Health, Development, and Anti-Malaria Association, Addis Ababa, Ethiopia
³ United States Agency for International Development, Addis Ababa, Ethiopia
⁴ USGS Earth Resources Observation and Science Center, Sioux Falls, SD, USA

Abstract
To understand the drivers and consequences of malaria in epidemic-prone regions, it is important to know whether epidemics emerge independently in different areas as a consequence of local contingencies, or whether they are synchronised across larger regions as a result of climatic fluctuations and other broad-scale drivers. To address this question, we collected historical malaria surveillance data for the Amhara region of Ethiopia and analysed them to assess the consistency of various indicators of malaria risk and determine the dominant spatial and temporal patterns of malaria within the region. We collected data from a total of 49 districts from 1999–2010. Data availability was better for more recent years and more data were available for clinically diagnosed outpatient malaria cases than confirmed malaria cases. Temporal patterns of outpatient malaria case counts were correlated with the proportion of outpatients diagnosed with malaria and confirmed malaria case counts. The proportion of outpatients diagnosed with malaria was spatially clustered, and these cluster locations were generally consistent from year to year. Outpatient malaria cases exhibited spatial synchrony at distances up to 300 km, supporting the hypothesis that regional climatic variability is an important driver of epidemics. Our results suggest that decomposing malaria risk into separate spatial and temporal components may be an effective strategy for modelling and forecasting malaria risk across large areas. They also emphasise both the value and limitations of working with historical surveillance datasets and highlight the importance of enhancing existing surveillance efforts.

Keywords malaria epidemics, surveillance, climate, environment, spatial autocorrelation, spatial synchrony

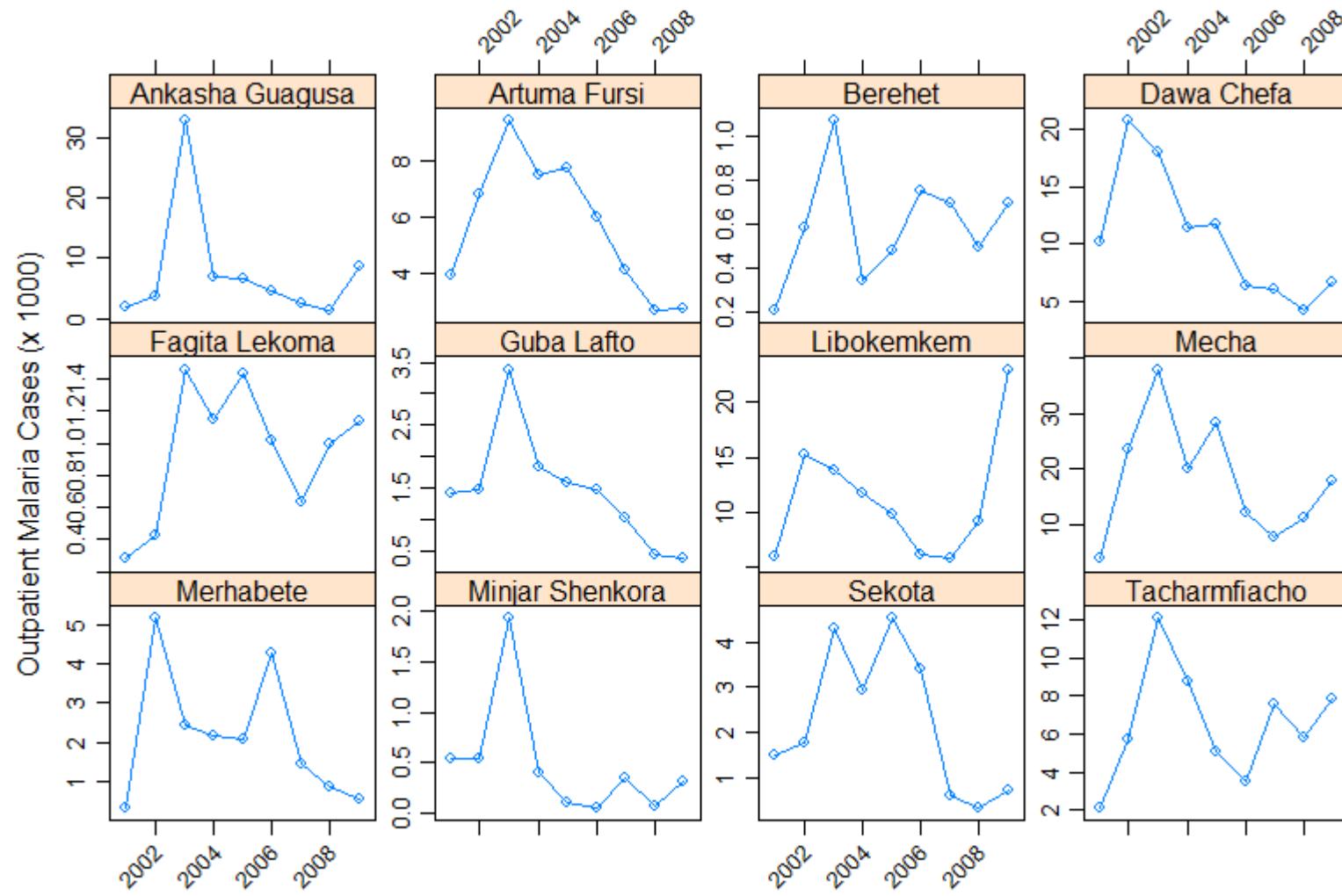
Introduction
Malaria is one of the most common infectious diseases in the world and a major public health problem throughout sub-Saharan Africa. Within this region, malaria epidemics occur most frequently in highland and semi-arid zones and are often associated with interannual fluctuations in rainfall and temperature (Abebe 2007). These epidemics can be particularly devastating because they occur in areas where large portions of the population lack immunity to malaria. Better information about the timing and locations of malaria epidemics would allow for more accurate targeting of resources for malaria prevention, control and treatment. Therefore, there is general agreement about the importance of malaria surveillance for early detection of epidemics and the potential value of malaria early-warning systems based on environmental monitoring and seasonal climate forecasting (DaSilva *et al.* 2004). To develop effective early-detection and early-warning systems, it is essential to first understand the underlying pattern and scale of malaria occurrence in both time and space. In particular, it is important to know whether epidemics emerge independently in different areas as a consequence of local contingencies, or whether they are synchronised across larger regions as a result of climatic fluctuations and other broad-scale drivers.
As with other diseases, malaria is spatially autocorrelated over a range of scales from local to global (Brooker *et al.* 2004; Ernst *et al.* 2006; Hay *et al.* 2009). The geographic distribution of malaria is strongly influenced by climate and is restricted to areas where there is enough rainfall to create mosquito breeding habitats, sufficient humidity for high activity and survival of vector mosquitoes, and high temperatures that support rapid

1192 © 2012 Blackwell Publishing Ltd

Wimberly *et al.* (2012) Spatial synchrony of malaria outbreaks in a highland region of Ethiopia. *Tropical Medicine and International Health*. 17: 1192–1201.

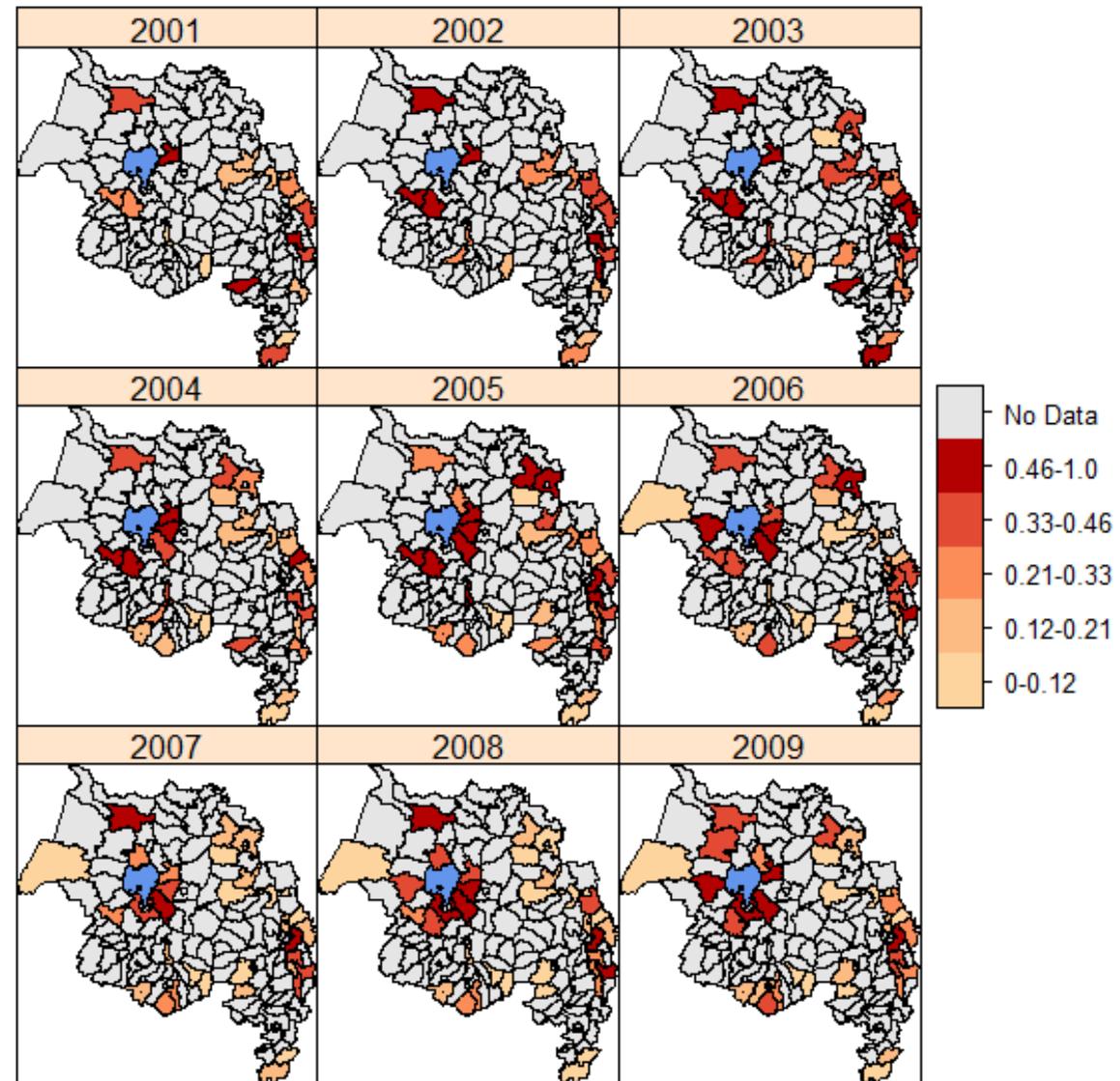
Outpatient Malaria Cases

Total number of cases from Sept-Dec



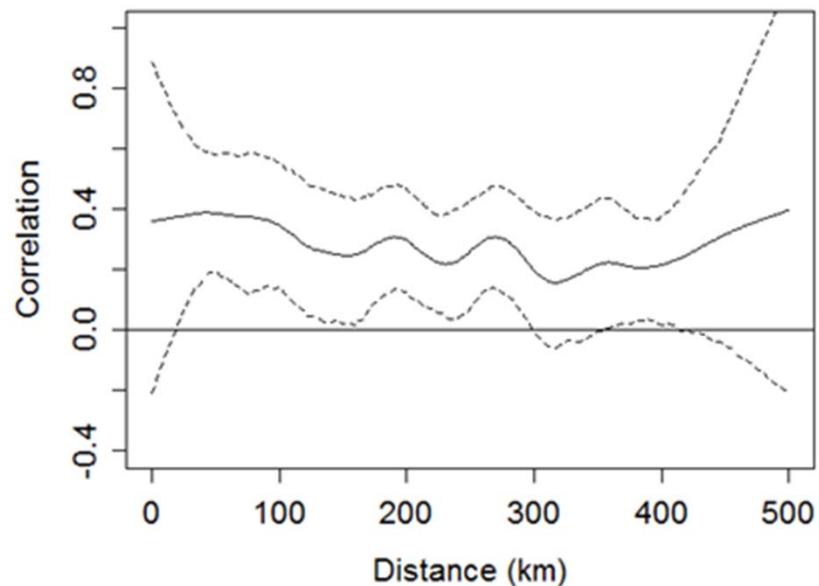
Proportion of outpatients diagnosed with malaria (POM) displayed as a series of *choropleth maps*

Statistical tests confirmed significant spatial clustering (positive spatial autocorrelation) of POM in most years



Spatial Synchrony

- Positive spatial synchrony at distances out to 300 km (and possibly longer)
- Confirms spatial structure in the *interannual variability* of malaria incidence
- Provides indirect evidence of a linkages between climatic anomalies and malaria risk



Remotely-sensed metrics of climatic variability

- Are remotely sensed variables significantly associated with temporal patterns of malaria risk?
- What are the temporal lags at which each environmental variable is associated with malaria risk?
- Does the addition of remote sensing covariates improve time series model fits compared to models based only on historical case data?

Malaria Journal | Abstract | Remote sens... +

www.malariajournal.com/content/11/1/165/abstract

Log on

MALARIA JOURNAL IMPACT FACTOR 3.19

Home Articles Authors Reviewers About this journal My Malaria Journal

Research Highly accessed Open Access

Remote sensing-based time series models for malaria early warning in the highlands of Ethiopia

Alemayehu Midekisa, Gabriel Senay, Geoffrey M Henebry, Paulos Semuniguse and Michael C Wimberly

For all author emails, please [log on](#).

Malaria Journal 2012, **11**:165 doi:10.1186/1475-2875-11-165
Published: 14 May 2012

Abstract (provisional)

Background
Malaria is one of the leading public health problems in most of sub-Saharan Africa, particularly in Ethiopia. Almost all demographic groups are at risk of malaria because of seasonal and unstable transmission of the disease. Therefore, there is a need to develop malaria early-warning systems to enhance public health decision making for control and prevention of malaria epidemics. Data from orbiting earth-observing sensors can monitor environmental risk factors that trigger malaria epidemics. Remotely sensed environmental indicators were used to examine the influences of climatic and environmental variability on temporal patterns of malaria cases in the Amhara region of Ethiopia.

Methods
In this study seasonal auto regressive integrated moving average (SARIMA) models were used to quantify the relationship between malaria cases and remotely sensed environmental variables, including rainfall, land-surface temperature (LST), vegetation indices (NDVI and EVI), and actual evapotranspiration (ETa) with lags ranging from one to three months. Predictions from the best model with environmental variables were compared to the actual observations from the last 12 months of the time series.

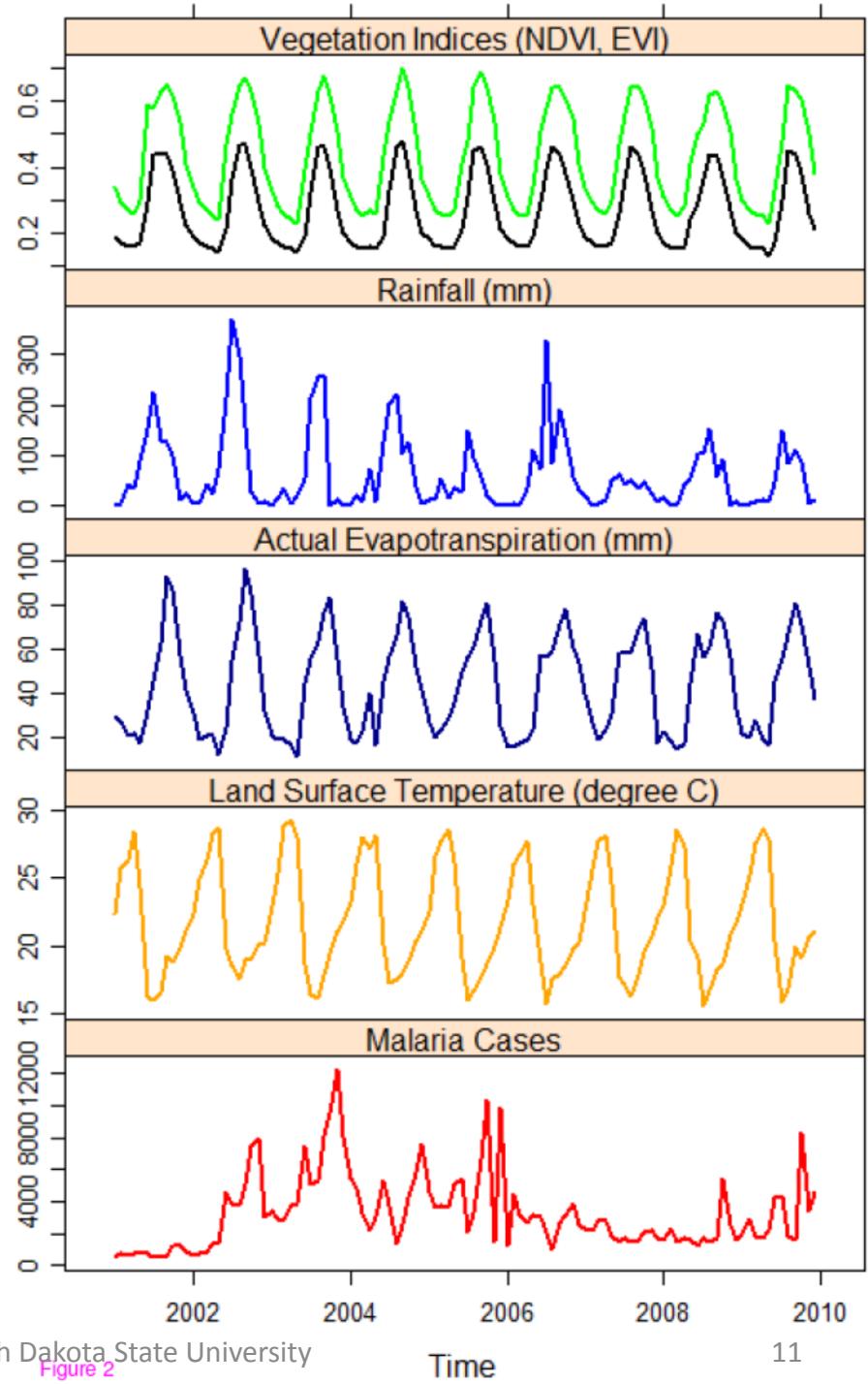
Results
Malaria cases exhibited positive associations with LST at a lag of one month and positive associations with indicators of moisture (rainfall, EVI and ETa) at lags from one to three months. SARIMA models that included these environmental covariates had better fits and more accurate predictions, as evidenced by lower AIC and RMSE values, than models without environmental covariates.

Conclusions
Malaria risk indicators such as satellite-based rainfall estimates, LST, EVI, and ETa exhibited significant lagged associations with malaria cases in the Amhara region and improved model fit and prediction accuracy. These variables can be monitored frequently and extensively across large geographic areas using data from earth-observing sensors to support public health decisions.

The complete article is available as a [provisional PDF](#). The fully formatted PDF and HTML versions are in production.

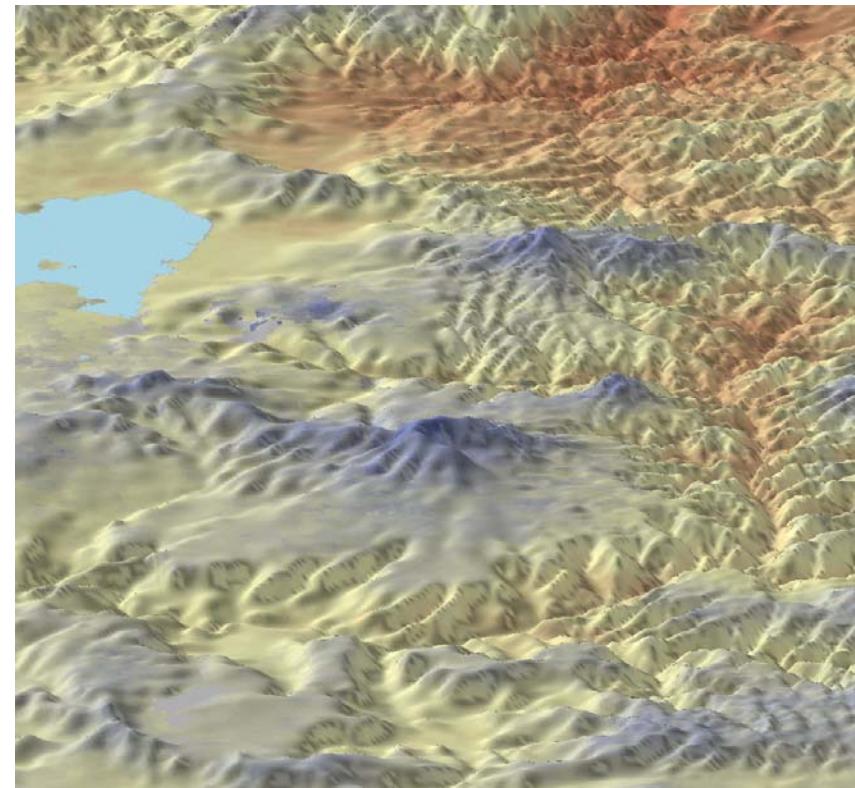
Midekisa et al. (2012) Remote sensing-based time series models for malaria early warning in the highlands of Ethiopia. [Malaria Journal](#) **11**: 165.

- Woreda-level summaries of climatic variables and surveillance data
- Time Series Analysis
- Monthly Environmental Metrics and Case data
 - Seasonality
 - Interannual Variability
 - Trend



Independent Variables – Land Surface Temperature (LST)

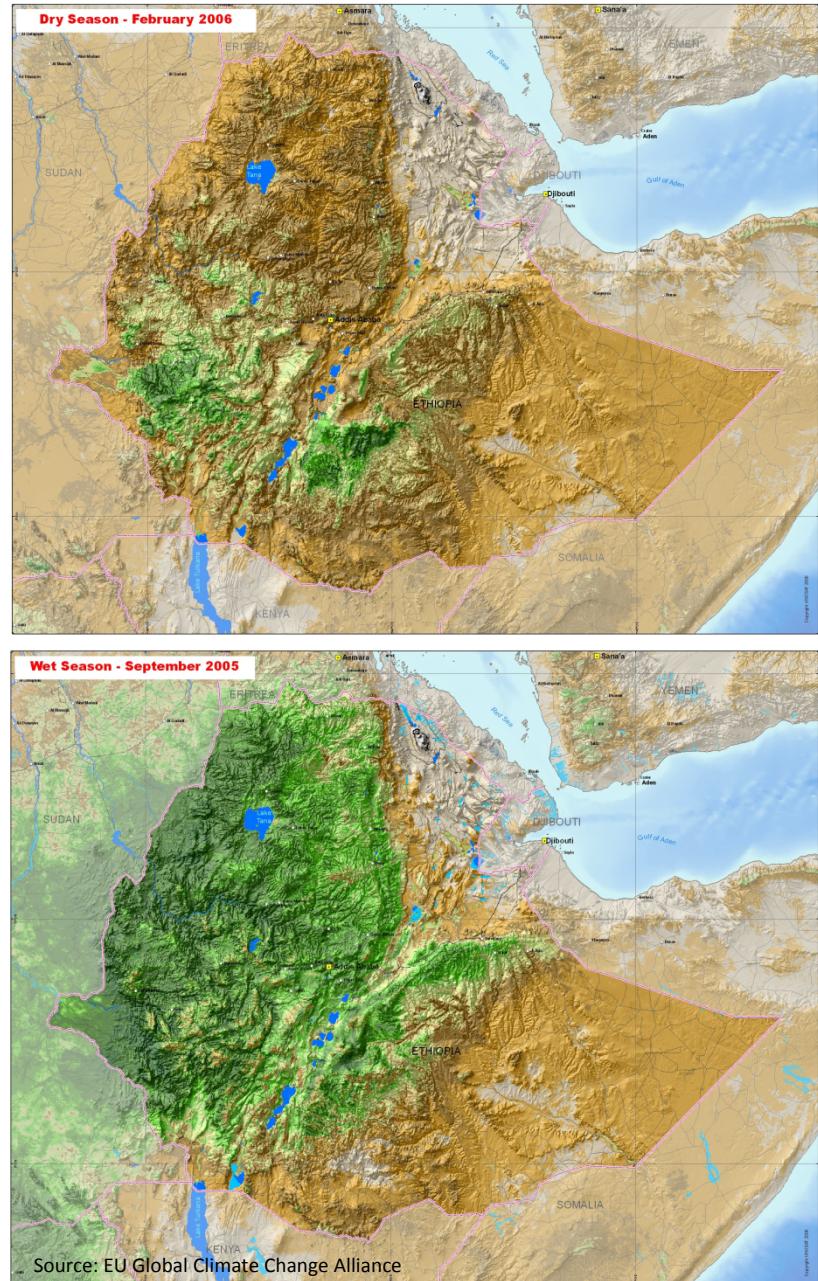
- Temperature of the earth's surface
- Sensitive to both air temperature and land cover
- MODIS Terra
- 8-day temporal resolution, 1 km spatial resolution



MODIS Terra land surface temperature (red=warm, blue=cool)

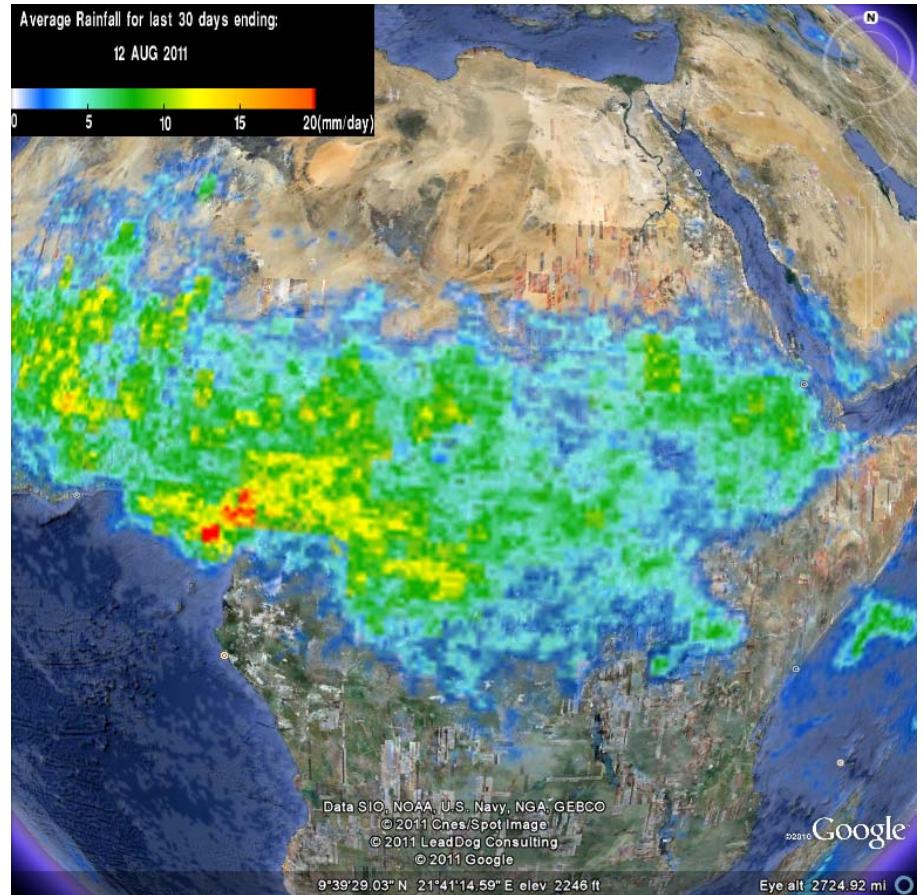
Independent Variables – Normalized Difference Vegetation Index (NDVI)

- Indicator of actively photosynthesizing vegetation
- Sensitive to a variety of environmental factors
- MODIS Terra/Aqua BRDF-corrected reflectance
- 8-day temporal resolution, 1 km spatial resolution



Independent Variables – Rainfall

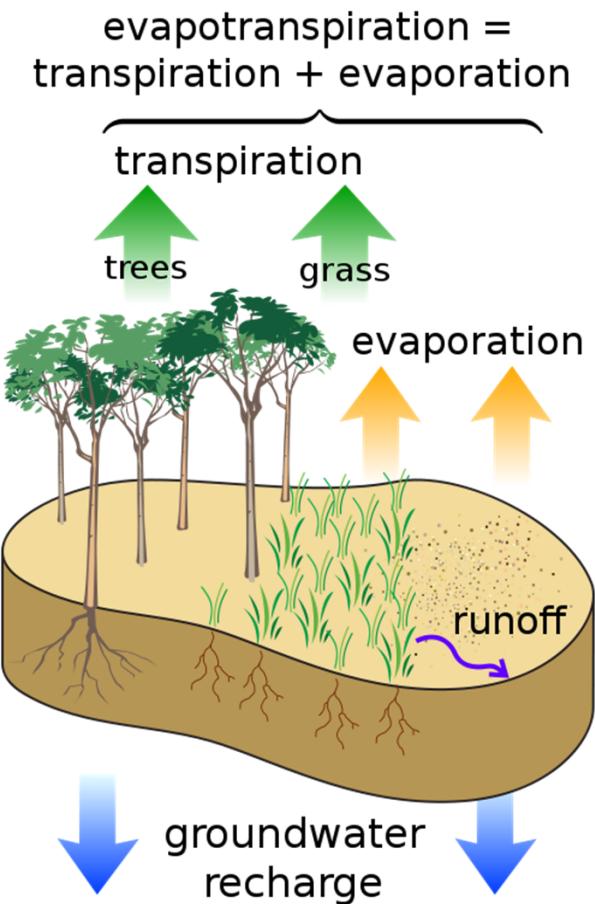
- Tropical Rainfall Monitoring Mission (TRMM)
- Synthesizes multiple data sources to estimate rainfall
- 1-day (8-day) temporal resolution, 0.25° spatial resolution
- Data Accessed via Giovanni using TOVAS



TRMM rainfall average for the last 30 days, August 12, 2011

Independent Variables – Actual Evapotranspiration (ET_a)

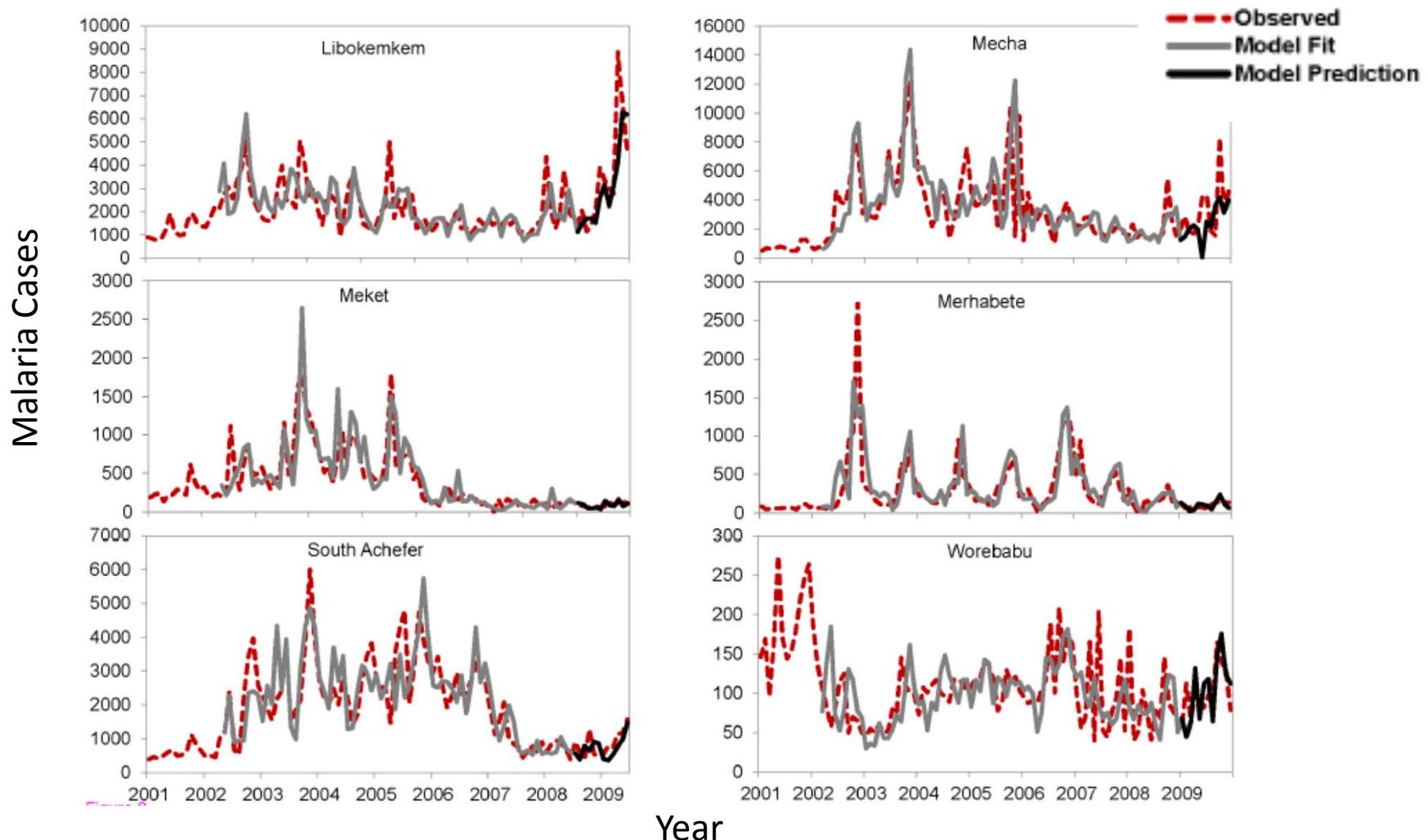
- Sensitive to soil moisture availability
- Modeled using the simplified surface energy balance method developed by Dr. Gabriel Senay
- 8-day temporal resolution, 1 km spatial resolution



Approaches to Time Series Analysis

- Monthly Differencing
 - Trend removal
- Seasonal Differencing
 - Seasonality removal
- Lagged associations with environment variables
 - How will temperature and precipitation fluctuations during the current time period influence malaria risk during future time periods
- Autoregression
 - Lagged associations with malaria cases in preceding months

Observed, Fitted, and Predicted Malaria Cases for 6 of the 12 Woredas Studied



Summary of Results

- Temperature, precipitation, and evapotranspiration anomalies in a given month influence malaria risk in future months
- The influences of the remotely sensed climatic variables were consistent across sites
 - Shorter for temperature (1 month)
 - Longer for precipitation and other moisture variables (2-3 months)
- Models fit was improved by incorporating remotely-sensed environmental variables in to the models
- Models had relatively high forecasting accuracy, but only if lagged case data was used to make the predictions (autoregressive term)

Remotely-Sensed Environmental Risk Factors

- Identify environmental risk factors associated with malaria outbreaks using satellite remote sensing
 - Focus on the main malaria season (Sept-Dec)
 - Predict interannual variability in malaria risk
 - Are remotely sensed environmental anomalies earlier in the calendar year (Jan-Aug) associated with increased malaria risk at the end of the year?

International Environmental Modelling and Software Society (IEMSS)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
<http://www.iemss.org/society/index.php/femsa-2012-proceedings>

A Computer System for Forecasting Malaria Epidemic Risk Using Remotely-Sensed Environmental Data

Michael C. Wimberly¹, Ting-Wu Chuang¹, Geoffrey M. Henebry¹, Yi Liu²,

Alemayehu Midekisa³, Paulos Semuniguse³, Gabriel Senay⁴

¹South Dakota State University, Geographic Information Science Center of Excellence, Brookings, SD USA

²South Dakota State University, Department of Electrical Engineering and Computer Science, Brookings SD USA

³Health, Development, and Anti-Malaria Association, Addis Ababa, Ethiopia

⁴United States Geological Survey, Earth Resource Observation and Science (EROS) Center, Sioux Falls, SD USA

Abstract: Epidemic malaria is a major public health problem in the highlands of East Africa. Identifying the climatic triggers that increase malaria risk affords a basis for developing environmentally-driven early warning systems. Satellite remote sensing provides a wide range of environmental metrics that are sensitive to temperature, rainfall, and other climatic variables. The goals of this study were to develop a computer application for automatically acquiring and processing remote sensing data, and to test the utility of these data for modelling and forecasting malaria epidemics in the Amhara region of Ethiopia. The application was programmed using JAVA for user interface development and overall system control. Spatial analyses were carried out using Python scripts to call ArcGIS geoprocessing functions, and PostgreSQL was used to store and manipulate the resulting data summaries. Remotely-sensed variables included land surface temperature from MODIS/Terra, vegetation indices computed using MODIS nadir BRDF-adjusted reflectance, precipitation estimates from the Tropical Rainfall Measuring Mission, and actual evapotranspiration modelled using the simplified surface energy balance method. Historical remote sensing data from 2000-2010 were summarized at the district level by 8-day MODIS composite periods and transformed to deviations from their 11-year means. Time series of monthly malaria outpatient cases were collected for 19 districts in the Amhara region and used to compute risk indices for the main epidemic season from September-December. Malaria epidemics during this season were associated with a higher-than-normal number of malaria cases in May-June, higher-than-normal rainfall in January-May, and warmer-than-normal temperatures in May-June. A cross-validated statistical model containing these variables predicted more than 50% of the variability in malaria relative risk. Continued environmental monitoring using satellite remote sensing will allow us to forecast the environmental risk of malaria epidemics in future years and validate these initial results.

Keywords: Malaria; early warning; remote sensing; geoinformatics.

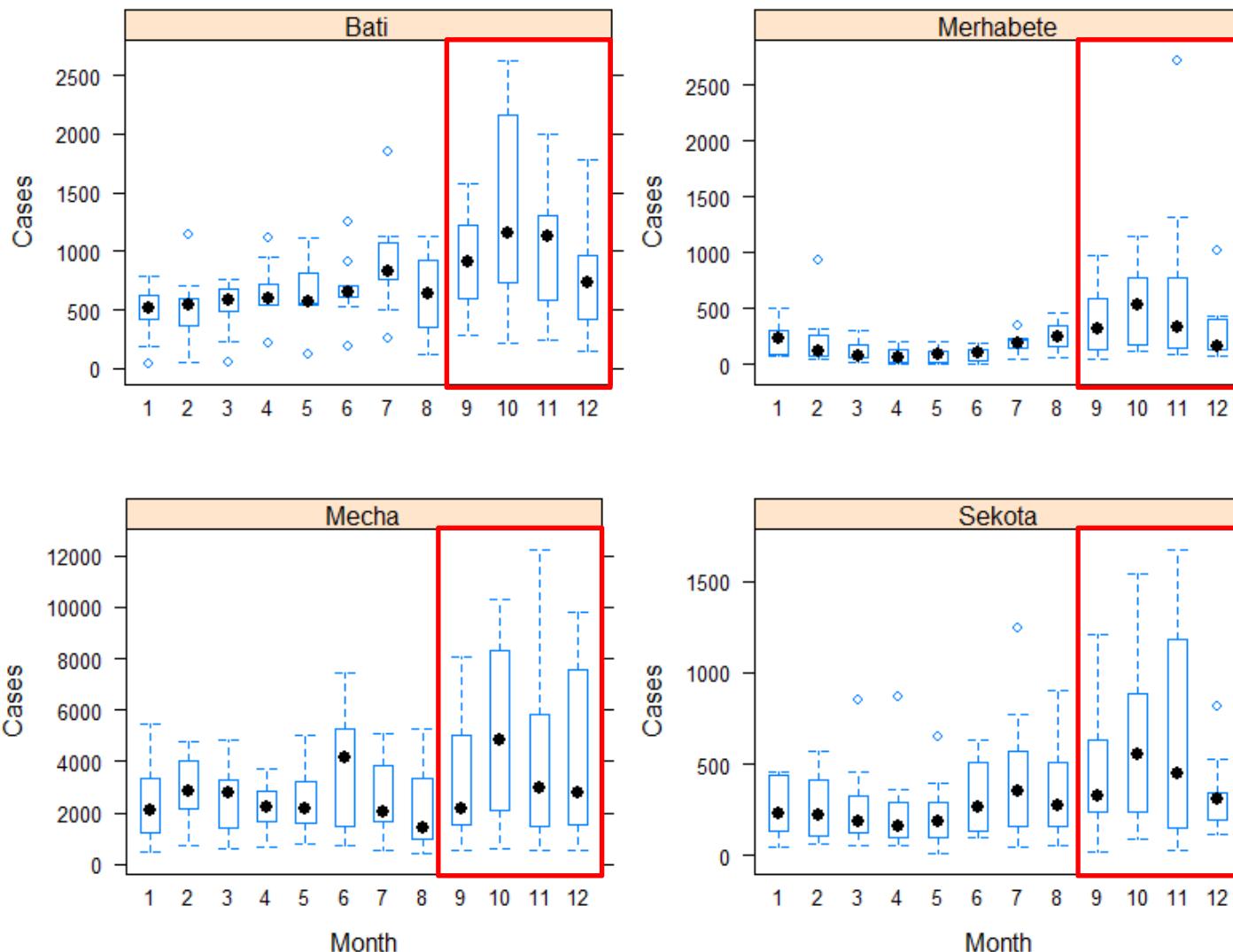
1 INTRODUCTION

Malaria is a globally important disease that imposes an immense public health burden throughout the developing world, particularly in sub-Saharan Africa. Marginal environments that support unstable transmission, such as highland and semi-arid regions, pose a particular challenge for malaria control and prevention [Abeku, 2007]. Although malaria transmission in these areas is low and often seasonal, interannual fluctuations in rainfall and temperature can increase transmission rates and trigger devastating epidemics. Because of the low immunity

Wimberly et al. (2012). [A computer system for forecasting malaria epidemic risk using remotely-sensed environmental data](#). Proceedings of the International Congress on Environmental Modelling and Software. Leipzig, Germany, July 1-5.

Seasonality of Malaria

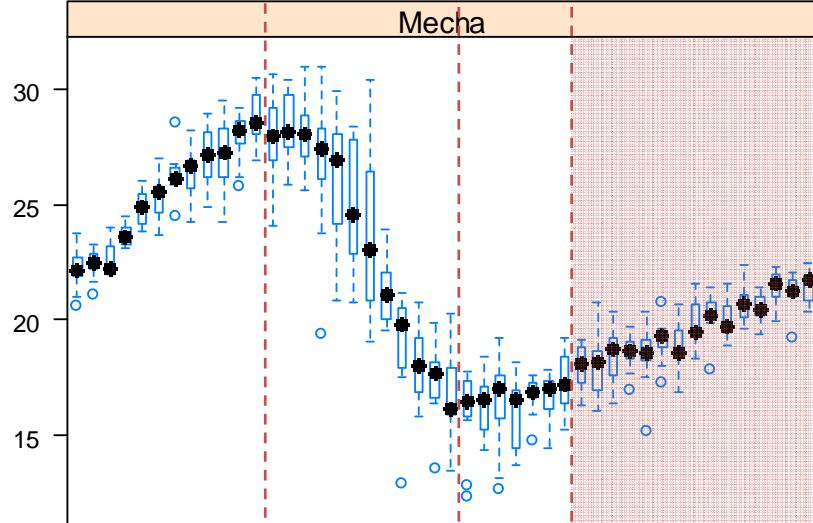
Outpatient Cases from Four Woreda



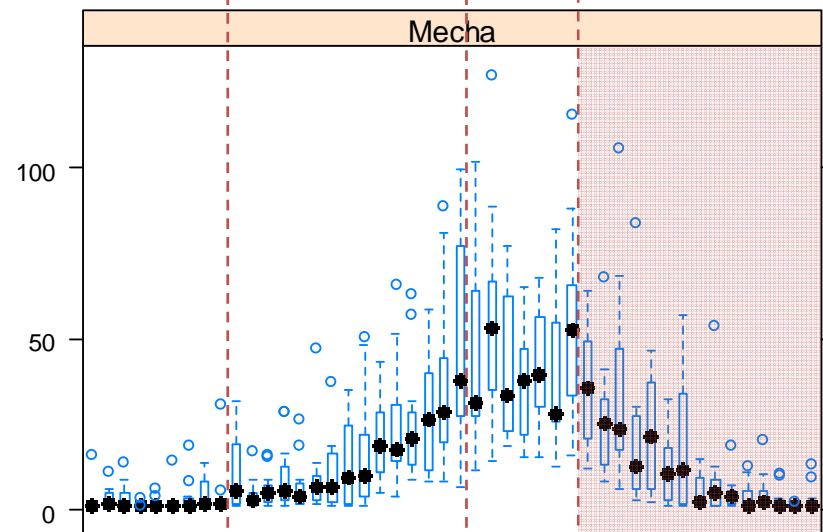
Seasonality of Climate

Mecha Woreda

April July September



March July September



MODIS Land Surface
Temperature

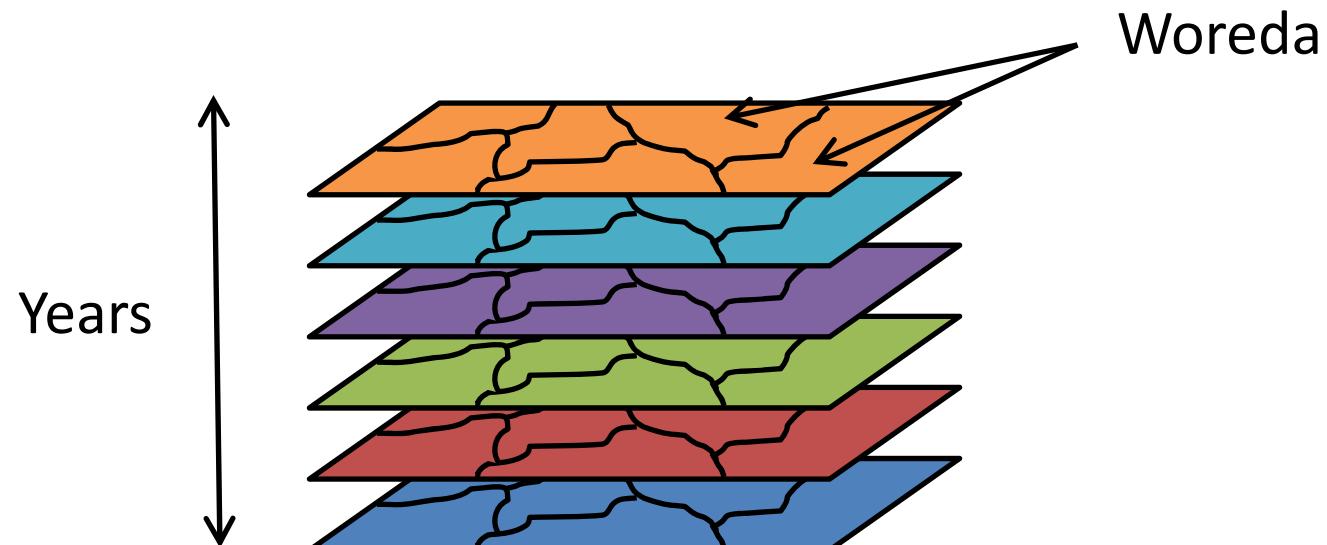
TRMM Rainfall

Dependent Variable – Relative Risk

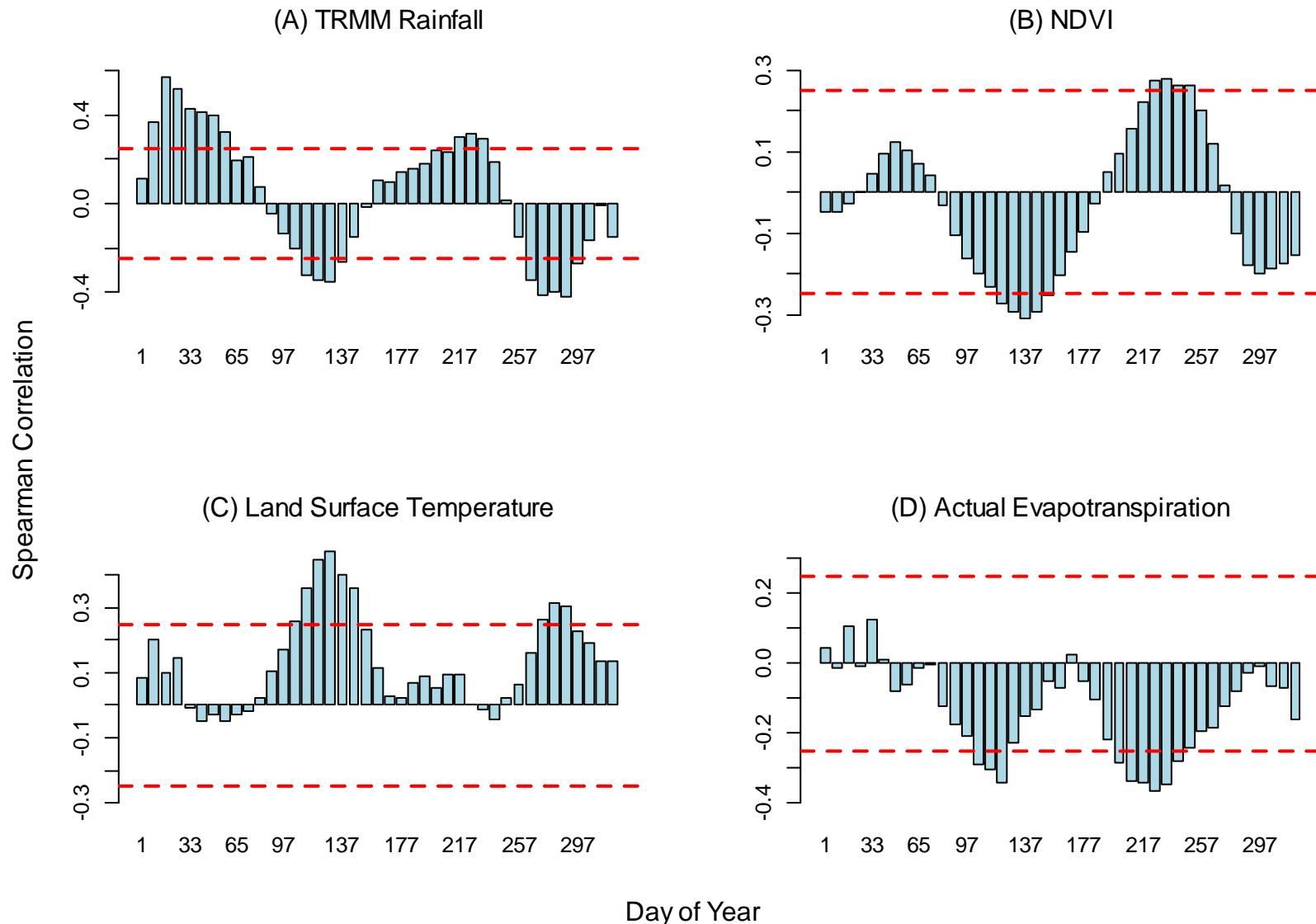
- $LRR_{ij} = \text{Observed Risk}/\text{Expected Risk}$
- $LRR_{ij} = \ln\left(\frac{\text{CASE}_{ij}}{\text{POP}_i}\right) / \overline{\ln\left(\frac{\text{CASE}_i}{\text{POP}_i}\right)}$
- $LRR_{ij} = \ln\left(\text{CASE}_{ij} / \overline{\text{CASE}_i}\right)$
- $LRR_{ij} = \ln(\text{CASE}_{ij}) - \ln(\overline{\text{CASE}_i})$
 - CASE = Number of outpatient cases from September-December
 - POP = Population at risk
 - i indexes woreda, j indexes years

Environmental Anomalies: Deviation Formula

- $DRSI_{ij} = 100 \times \frac{RSI_{ij} - \overline{RSI}_i}{\overline{RSI}_i}$
 - RSI = Remote Sensing Index
 - i indexes woreda, j indexes years

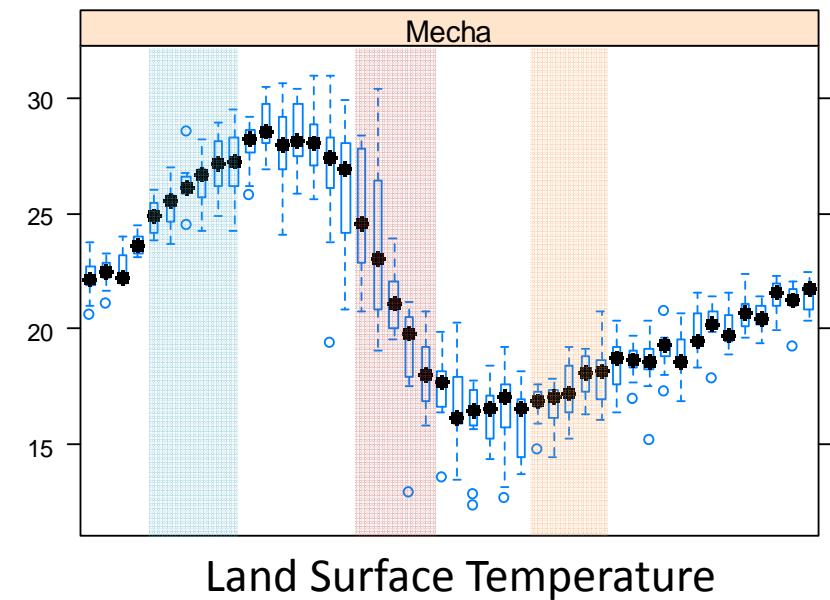
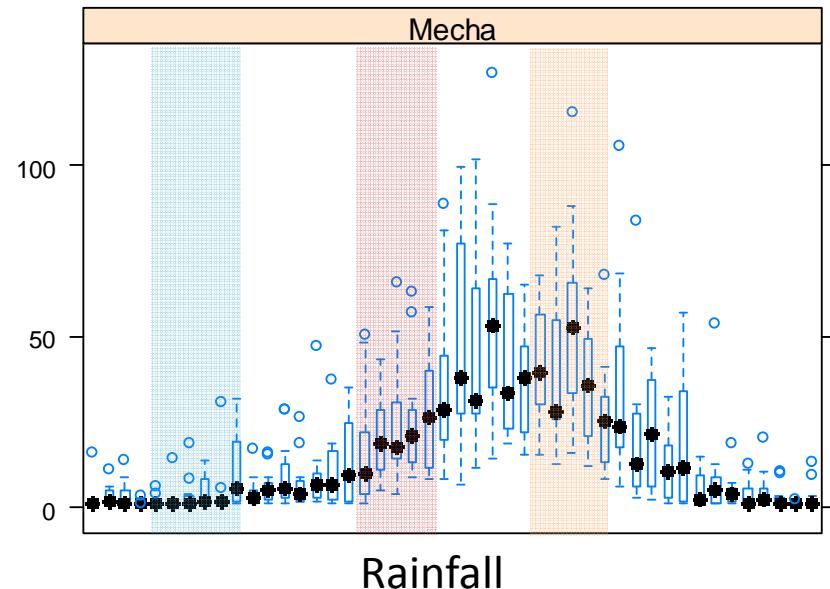


Environmental Anomalies – Correlations with Sept-Dec Malaria Relative Risk



Summary – Environmental Risk Factors

- Prior to the peak malaria season (January-August)
 - Higher than average rainfall in February
 - Lower than average rainfall/higher temperature in June
 - Higher than average rainfall in September
- Meteorological “trigger points” that set the stage for upcoming epidemics



Models of Relative Risk Based on Environmental Anomalies Prior to the Start of the Rainy Season

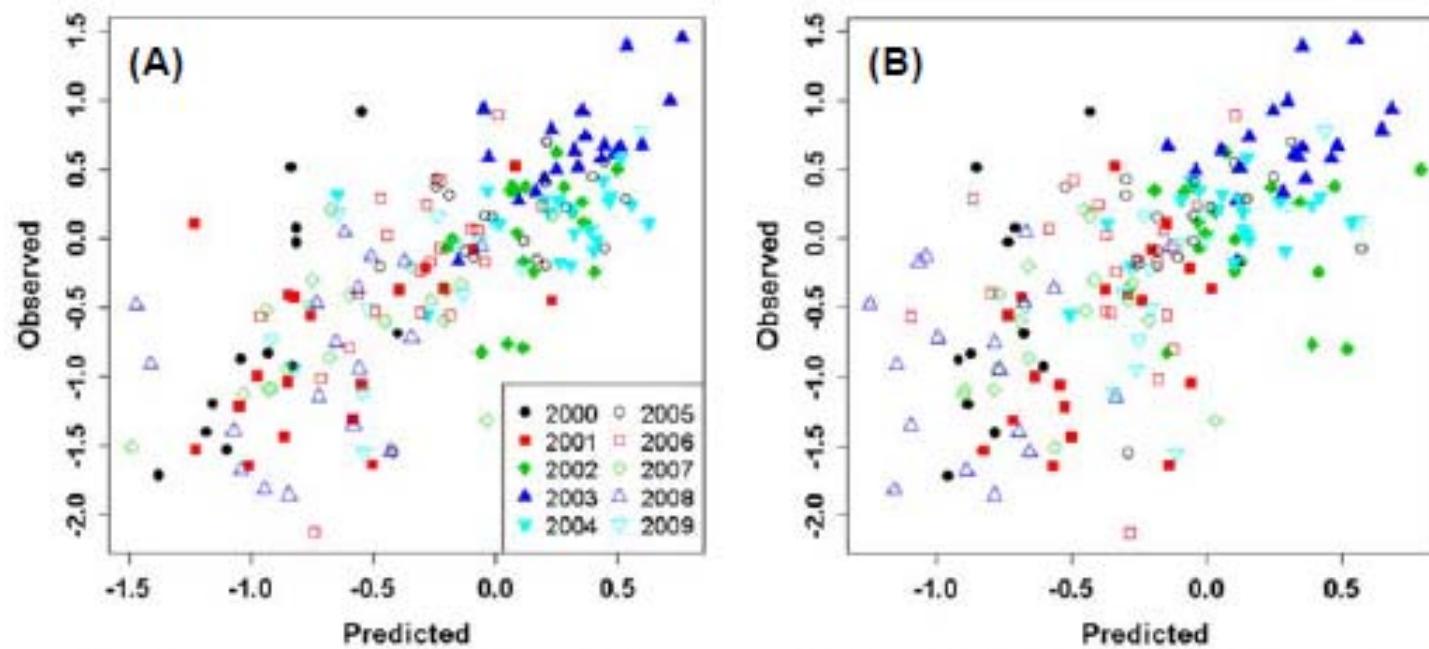
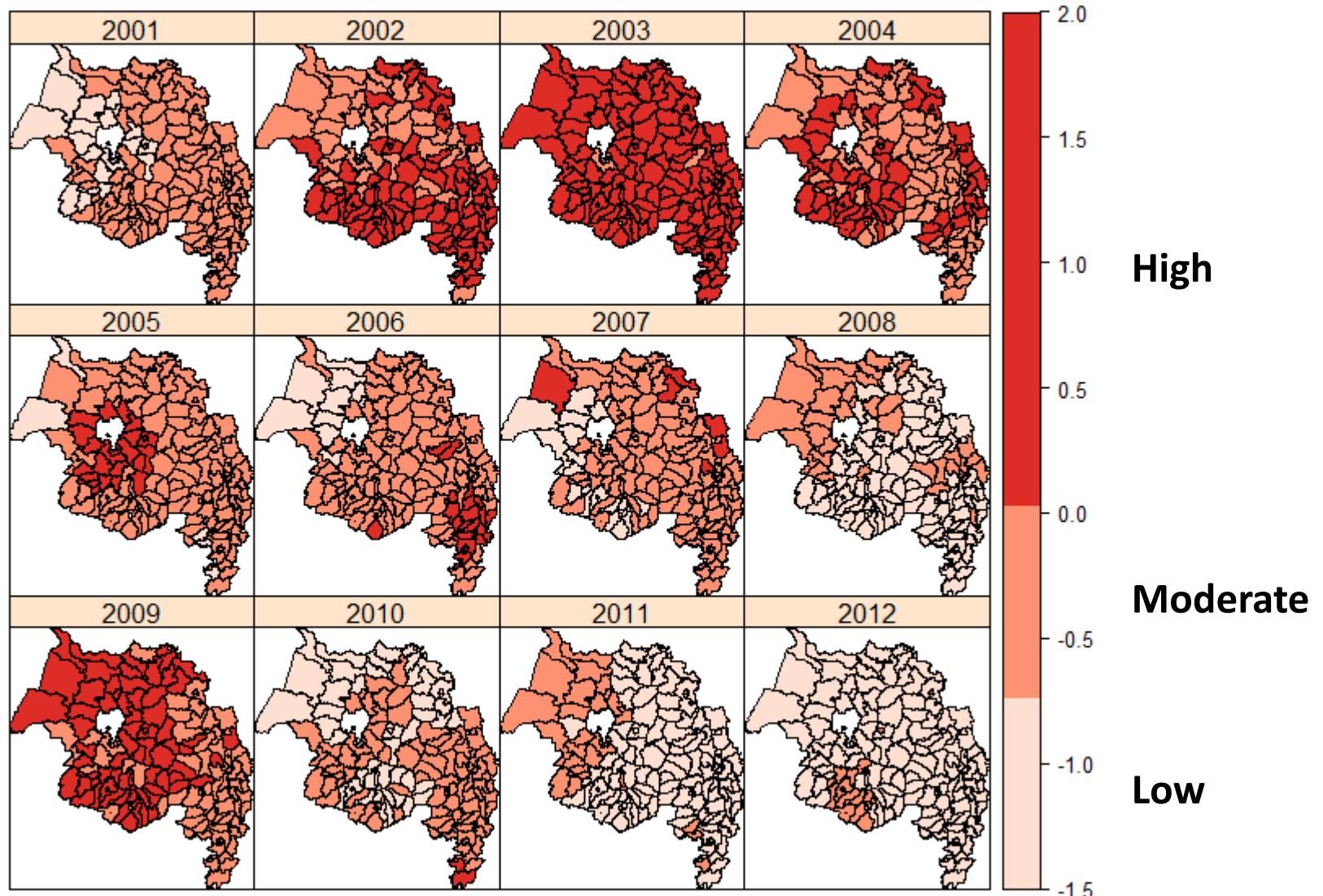


Figure 3: Cross-validation of a model of relative risk of malaria epidemics during September-December (LRR_p). (A) Predictions based on remotely sensed environmental variables and malaria relative risk during May-June (LRR_e). (B) Predictions based on remotely sensed environmental variables alone.

Predicted Relative Risk

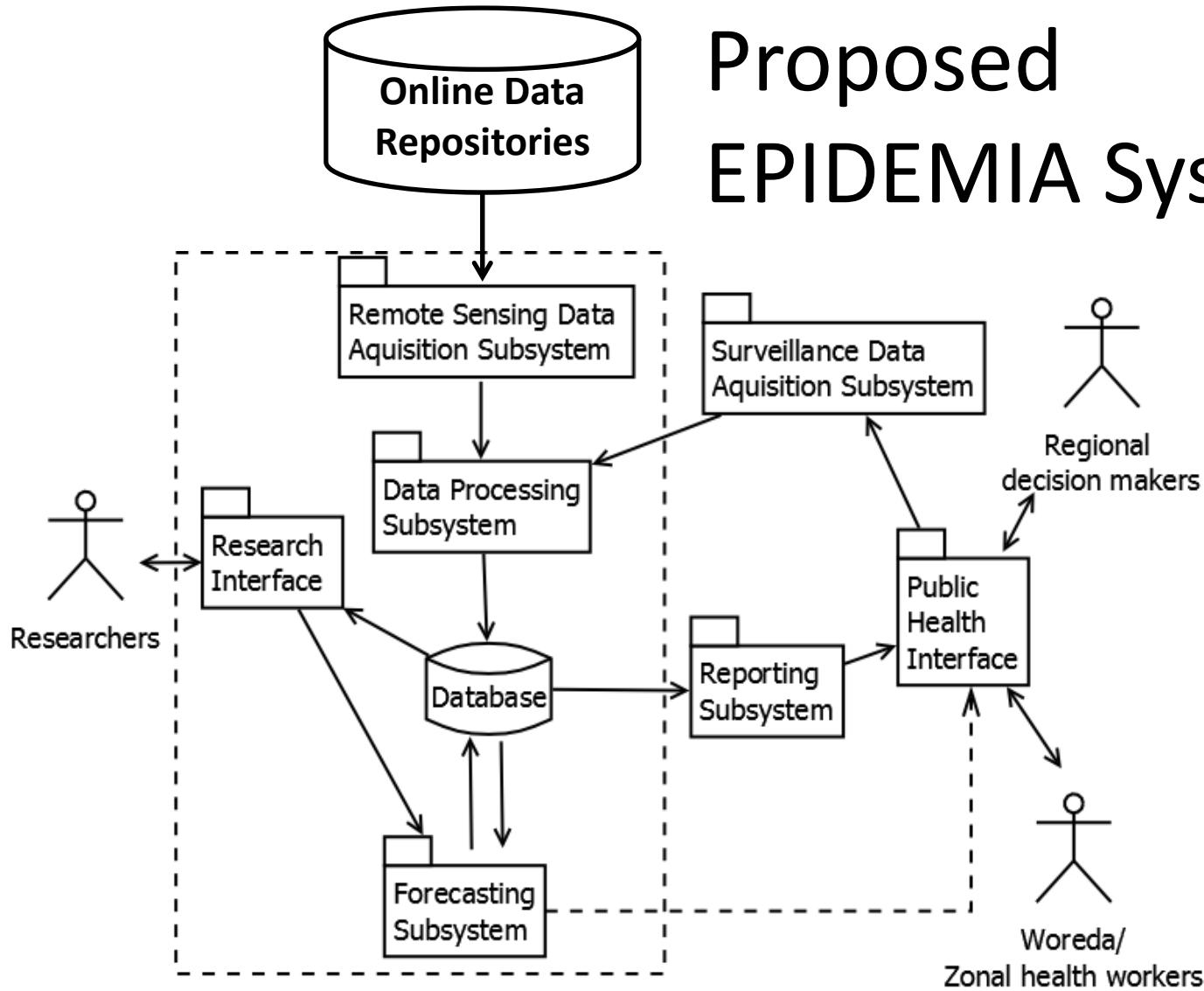


Next Steps

- Continue to update and refine models for malaria risk mapping and forecasting
- Develop new remote sensing products for mapping surface water
- Improve automation of remote sensing data processing
- Devise tools and techniques for integrating disease surveillance and environmental monitoring



Proposed EPIDEMIA System



Epidemic Prognosis Incorporating Disease and Environmental Monitoring for Integrated Assessment (EPIDEMIA)

Acknowledgements

- South Dakota State University
 - Alemayehu Midekisa, GISCeCE
 - Ting-Wu Chuang, GISCeCE
 - Geoffrey Henebry, GISCeCE
 - Mike Hildreth, Depts. of Biology/Microbiology and Veterinary Science
 - Yi Liu, Dept. of Electrical Engineering and Computer Science
- USGS Center for EROS
 - Gabriel Senay
- Health, Development, and Anti-Malaria Association
 - Abere Mihretie
 - Hiwot Teka
 - Paulos Semunigus
- Federal Democratic Republic of Ethiopia Ministry of Health
- Amhara Regional Health Bureau
- Funding
 - NIH/NIAID
 - NASA



<http://globalmonitoring.sdsstate.edu/eastweb/>